A Review and Prospects of Quantum Teleportation

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Abstract—**Teleportation is a new and exciting field of future communication. We know that security in data communication is a major concern nowadays. Among the encryption technologies that are available at present, shared key is the most reliable which depends on secure key generation and distribution. Teleportation/ Entanglement is a perfect solution for secure key generation and distribution, as for the no cloning theorem of quantum mechanics any attempt to intercept the key by the eavesdropper will be detectable immediately. We have reviewed and presented Teleportation concept, its process, road blocks, and successes that are achieved recently in a straightforward manner and showed that Teleportation is going to be used practically for quantum key distribution in very near future by separating its unique features.**

Index Terms—**Teleportation, Entanglement, Bell State, Qubit, Quantum State**

I. INTRODUCTION

QUANTUM Teleportation is a process by which we can transfer the quantum state of a system and its correlation to another system [1]. Teleportation can deliver the subtle, unscannable kind of information and this information is totally different from ordinary information. Teleportation is developed, based on the concept of Quantum Entanglement. Entangled particles act here as a channel for transformation [2]. Teleportation/ Entanglement is exploited by parallel computing, quantum communication, cryptography technology, distributed computing [1]-[4] etc. Of them cryptography is the prosperous field where it would be possible to use Teleportation/Entanglement in an efficient and effective way, in very near future. In classical cryptography, we can use public key encryption or shared key encryption. But public key is vulnerable to attack by quantum computer, as quantum computer would be able to factor the prime product very quickly. Though shared key is secured but it requires many shared random numbers that can not be used more than once, hence the problem of distributing random numbers arises. Quantum Teleportation/Entanglement is therefore, to solve the problem. A completely secure quantum key can be generated and distributed (for communication and decoding of encrypted messages) using entangled photons has been demonstrated in [5]-[7]. Any eavesdropper's attempt to intercept the quantum key will alter the contents in a detectable way, enabling users to discard the compromised parts of the data. Research is going on to use Teleportation for Quantum Key Distribution. Quantum teleportation can be implemented with a quantum circuit that is much simpler than that required by any nontrivial quantum computational task. The state of an arbitrary qubit (quantum bit) can be teleported with as few as two quantum exclusive-or (controlled-not) gates. Thus, quantum teleportation is significantly easier to implement than quantum computing if we are concerned only with the complexity of the required circuitry. Short-distance quantum teleportation will play a role in transporting quantum information inside quantum computers.

In this paper we have reviewed and presented a very easy form to understand the Teleportation concept, its process, what limits the process, and recent developments. We build a simple framework for using Teleportation in Quantum key Distribution.

II. DESCRIPTION OF Q-TELEPORTATION

Quantum teleportation is based on the well-known concept of quantum entanglement. The word "entanglement" was used by Erwin Schrödinger in 1935 in a three-part paper [8]-[11]. Einstein, Podolsky and Rosen prompted these papers in their paper [12] that raised fundamental questions about quantum mechanics. EPR says that quantum theory allows certain correlations to exist between two physically distant parts of a quantum system. If there are such correlations then it is possible to predict the result of a measurement on one part of a system by looking at the other part. For this reason EPR argued that the predicted quantity should have a definite value even before it is measured, if quantum theory is complete and respects locality (a.k.a. causality). As it disallows such definite values prior to measurement EPR concluded that, from a classical perspective, quantum theory must be incomplete. Schrödinger's speech on this argument gives the modern view of quantum mechanics; he says that the wave function (a.k.a. quantum state vector) provides all the information there is

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about a quantum system. About the nature of entangled quantum states, Schrödinger [8]-[11] stated that, "The whole is in a definite state, the parts taken individually are not." This statement defines the essence of pure-state entanglement. Bell [13] later solved the EPR dilemma by deriving correlation which is violated in quantum mechanics but is satisfied within every model that is local and complete. Groundbreaking experimental work by Aspect et al. [14] along with further theoretical and experimental work done by others [15]-[21] demonstrated violations of the Bell inequalities. It can be concluded from recent theoretical and experimental work that an observed violation of a Bell inequality demonstrates the presence of entanglement in a quantum system. To better understand the concept of quantum entanglement/ teleportation, we will focus on the quantum wave function (a.k.a. quantum state function). Any quantum system such as a particle that possesses a position in space, energy, angular and linear momentum, and spin is completely described by a wave function $|\varphi\rangle$. Anything that we want to know about the particle is mathematically encoded within $|\varphi\rangle$. We never know the wave function completely because there is no measurement that can determine it completely. By measuring one of the properties of a quantum system, we can get a glimpse of the overall quantum state that is encoded within $|\varphi\rangle$. According to the quantum uncertainty principle, the act of doing such a measurement will destroy any ability to subsequently determine the other properties of the quantum system. That is why it is impossible to copy particles and reproduce them elsewhere via quantum teleportation. However one can recreate an unmeasured quantum state in another particle if he is prepared to sacrifice the original particle. This is done by exploiting the EPR process to circumvent the quantum uncertainty principle. EPR discovered if we measure one of the entangled sub-systems that will puts it into a particular quantum state, while instantaneously putting the other sub-system with which it is entangled into a corresponding quantum state, though the two sub-systems are separated by arbitrarily large distances in spacetime (even backwards in time!).

III. Q-Teleportation Process

Experimental work of Bennett et al. [22] followed by theoretical and experimental work of others [23]-[31] demonstrate the principle of quantum Teleportation in practice. This remarkable technical breakthrough settled once and for all the nagging question of whether quantum entanglement could be used to implement a teleportation process to transfer information between remotely distant quantum systems non-causally (i.e., at FTL speed).

We are now giving a simplified outline of the actual teleportation process which follows the outline of Bennett et al. [22] which is a multistep procedure by which any quantum state $|\chi\rangle$ of a particle or a photon (that correspond to an N-state system) is to be teleported from one location to another.

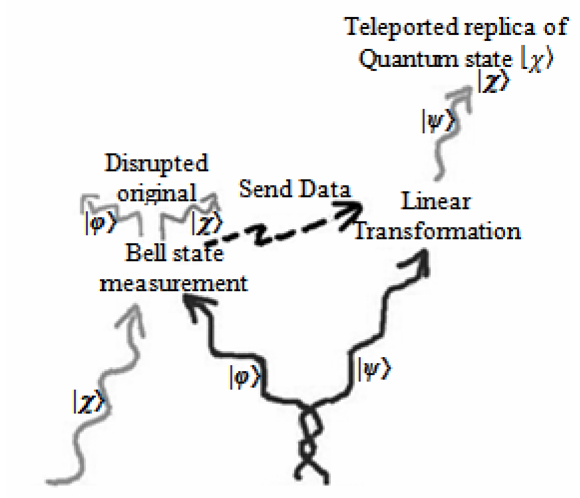

Fig. 1. Quantum Teleportation (Modified IBM Press Image)

Let quantum state $|\chi\rangle = \alpha\,|0\rangle + \beta|1\rangle$ of a particle is to be teleported from one location to another-

Step 1:

We prepare a pair of quantum subsystems $|\varphi\rangle$ and $|\psi\rangle$ in an EPR entangle state. John Bell proved that for a 2 q-bit quantum system there are only four possible entangled states, called the Bell states [32]:

$$\begin{aligned} |\Psi^{+}\rangle &= (|00\rangle + |11\rangle)/ \\ |\Psi^{-}\rangle &= (|00\rangle - |11\rangle)/ \\ |\Phi^{+}\rangle &= (|01\rangle + |10\rangle)/ \\ |\Phi^{-}\rangle &= (|01\rangle - |10\rangle)/ \end{aligned} \tag{1}$$

Step 2:

We now send $|\varphi\rangle$ to the location of sender "Alice". And send $|\psi\rangle$ to the location of receiver "Bob". These two subsystems are non-causally correlated via entanglement, but at this point they contain no information about $|\chi\rangle$.

The two subsystems are now like an open quantum channel that is ready to transmit information.

Step 3:

To perform the teleportation, now Alice brings the teleported state $|\chi\rangle$ into contact with the entangled state $|\varphi\rangle$ and performs a Bell state measurement on the combined system $|\chi\rangle|\varphi\rangle$.

Step 4:

Alice transmits to Bob a complete description of the outcome of the Bell state measurement using a conventional classical communication channel.

Step 5:

Let the outcome of Alice's Bell state measurement is $|\Phi+\rangle$ then Bob's photon is in the state: $|\psi\,\rangle = -\,\alpha\,|\,1\rangle + \beta\,|0\rangle$. So Bob now knows set of linear transformations (i.e., suitable unitary operation) to be applied on $|\psi\rangle$ to get exact replica of the state of $|\chi\rangle$. After linear transformation $|\psi\rangle$ is now in a state identical to the original state $|\chi\rangle$.

It is the quantum states of the particles/photons that are destroyed and recreated in the teleportation process and not the particles/photons themselves.

Decoherence Fundamentally Limits Q-Teleportation. To make the q-Teleportation scenario simplified we unrealistically assumed that Alice and Bob shared an EPR entangled pair that was free of noise or decoherence. An object's quantum states degrade by information leaks to or from the environment (i.e., environmental noise) through stray interactions with the object and this process is called decoherence. The quantum link (or EPR interaction) between a pair of systems is subject to noise or decoherence through photon loss or heating of the phonons. Decoherence imposes a fundamental limit on our ability to perform quantum information processing. Research is going on to see whether decoherence can be reduced, circumvented, or otherwise be (partially or totally) eliminated. Dür and Briegel [33] have taken the first step towards this goal at primary level by showing that fault tolerant quantum computation can be achieved.

IV. Q-TELEPORTATION CIRCUIT

For this circuit we shall need exclusive-or gate (XOR), single-qubit rotations L and R, and single-qubit conditional phase-shifts S and T. In terms of unitary matrices, the operations of L, R, S and T are -

$$L = \frac{1}{\sqrt{2}}\begin{pmatrix} 1 & -1 \\ 1 & 1 \end{pmatrix} \qquad R = \frac{1}{\sqrt{2}}\begin{pmatrix} 1 & 1 \\ -1 & 1 \end{pmatrix}$$
$$S = \begin{pmatrix} i & 0 \\ 0 & 1 \end{pmatrix} \qquad T = \begin{pmatrix} -1 & 0 \\ 0 & -i \end{pmatrix} \tag{2}$$

And quantum exclusive-or operation is given by matrix -

$$XOR = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{pmatrix} \tag{3}$$

Now consider the following quantum circuit [34]. Please disregard the dashed line for the moment.

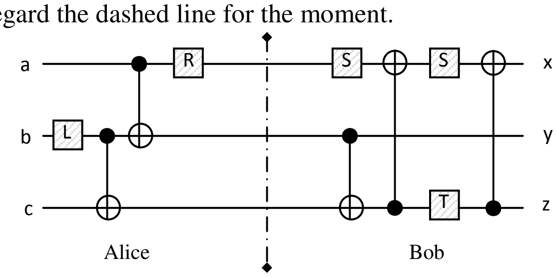

Fig. 2. Teleportation circuit.

Let $|\psi\rangle$ be an arbitrary one-qubit state. Consider what happens if we feed $|\psi 00\rangle$ in this circuit, that is if we set upper input a to $|\psi\rangle$ and both other inputs b and c to $|0\rangle$. It is an easy exercise to verify that state $|\psi\rangle$ will be transferred to the lower output z, whereas both other outputs x and y will come out in state $|\phi\rangle = (|0\rangle + |1\rangle)/\sqrt{2}$, that is the output will be $|\phi\phi\psi\rangle$. If we measure the two upper outputs in the standard basis ($|0\rangle$ versus $|1\rangle$), two random classical bits will be obtained in addition to quantum state $|\psi\rangle$ on the lower output.

Now, let us consider the state of the system at the dashed line. By a simple calculation we see that all three qubits are entangled. We should therefore be especially careful not to disturb the system at that point. Nevertheless, let us measure the two upper qubits, leaving the lower qubit undisturbed. This measurement results in two purely random classical bits u and v, bearing no correlation whatsoever with the original state $|\psi\rangle$. We now turn u and v back into quantum bits and reinject $|u\rangle$ and $|v\rangle$ in the circuit immediately after the dashed line.

Clearly the quantum state carried at the dashed line has been completely disrupted by this measurement-and-resend process. We would therefore expect this disturbance to play havoc with the final output of the circuit. Not at all! In the end, the state carried at xyz is $|uv\psi\rangle$. In other words, $|\psi\rangle$ is still obtained at z and the other two qubits, if measured, are purely random provided we forget the measurement outcomes at the dashed line. Another way of seeing this phenomenon is that the 2 outcome of the circuit will not be altered if the state of the upper two qubits leaks to the environment (in the standard basis) at the dashed line.

To turn this circuit into a quantum teleportation device, we need the ability to store qubits. Let us assume Alice prepares two qubits in state $|0\rangle$ and pushes them through the first two gates of the circuit.

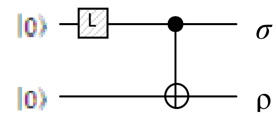

Fig 3. Segment of teleportation circuit.

She keeps the upper qubit σ in quantum memory and gives the other, ρ, to Bob. [We are not denoting these qubits by kets because they are not individual pure states: together they are in state $\Phi^+ = (|00\rangle + |11\rangle)/\sqrt{2}$. At some later time, Alice takes a mystery qubit in unknown state $|\psi\rangle$. In order to teleport this qubit to Bob, she releases σ from her quantum memory and pushes it together with the mystery qubit through the next two gates of the circuit. She measures both output wires to turn them into classical bits u and v.

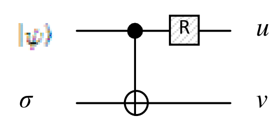

Fig. 4. Segment of teleportation circuit.

To complete teleportation, Alice has to communicate u and v to Bob by way of a classical communication channel. Upon reception of the signal, Bob creates quantum states $|u\rangle$ and $|v\rangle$ from the classical information received from Alice, he releases the qubit ρ he had kept in quantum memory, and he pushes all three qubits into his part of the circuit (on the right of the dashed line). Finally Bob may wish to measure the two upper qubit at x and y to make sure that he gets u and v; otherwise something went wrong in the teleportation apparatus. At this point, teleportation is complete as Bob's output z is in state $|\psi\rangle$. Note that this process works equally well if Alice's mystery qubit is not in a pure state. In particular, Alice can teleport to Bob entanglement with an arbitrary auxiliary system, possibly outside both Alice's and Bob's laboratories.

In practice, it is not essential for Bob to use the quantum circuit shown right of the dashed line at all. Instead, he may choose classically one of 4 possible rotations to apply to the qubit he had kept in quantum memory, depending on the 2 classical bits he receives from Alice. (This would be more in tune with the original teleportation proposal [35].) This explains the simplicity that quantum teleportation can be achieved at the cost of only two quantum exclusive-ors: those of Alice. Nevertheless, the unitary version of Bob's process given here may be more appealing than choosing classically among 4 courses of action if teleportation is used inside a quantum computer.

V. Use of Q-Teleportation in QKD

To explain the use of Quantum Teleportation in Quantum Key Distribution (QKD) here we present QKA (Quantum key agreement) protocol [36] which works as follow: Suppose the communicators, i.e. Alice and Bob, want to generate a private key over a public channel.

Step 1:

Alice first generates an EPR correlation pair locally written as [37]:

$$|\psi^-\rangle_{ab} = \frac{1}{\sqrt{2}}(|0\rangle_a|1\rangle_b - |1\rangle_a|0\rangle_b) \quad (4)$$

where *a* and *b* denote two photons. Then she sends photon *b* to Bob while keeping photon *a* in her hand.

Step 2:

If Bob receives photon b, he then prepares two photons *c* and *d* in the state:

$$|\phi\rangle_c = |\phi\rangle_d = \alpha|0\rangle + \beta|1\rangle = \binom{\alpha}{\beta} \quad (5)$$

where α and β are amplitudes known to Bob. Then the system composed of photons *a*, *b* and *c* is in the state [37]:

$$|\psi\rangle_{abc} = \frac{1}{2}\begin{bmatrix} |\psi^-\rangle_{bc}(-\alpha|0\rangle - \beta|1\rangle)_a \\ +|\psi^+\rangle_{bc}(-\alpha|0\rangle + \beta|1\rangle)_a \\ +|\phi^-\rangle_{bc}(\beta|0\rangle + \alpha|1\rangle)_a \\ +|\phi^+\rangle_{bc}(-\beta|0\rangle + \alpha|1\rangle)_a \end{bmatrix} \quad (6)$$

where $|\psi^\pm\rangle_{bc} = 1/\sqrt{2}(|0\rangle_b|1\rangle_c \pm |1\rangle_b|0\rangle_c)$, $|\phi^\pm\rangle_{bc} = 1/\sqrt{2}(|0\rangle_b|1\rangle_c \pm |1\rangle_b|0\rangle_c)$. Depending on Bob's measurement outcome, Alice's photon a will end up in one of the following four possible states $\binom{-\alpha}{-\beta}$, $\binom{-\alpha}{\beta}$, $\binom{\beta}{\alpha}$ and $\binom{-\beta}{\alpha}$ with equal probability. Suppose the four possible states $|\psi^-\rangle_{bc}$, $|\psi^+\rangle_{bc}$, $|\phi^-\rangle_{bc}$ and $|\phi^+\rangle_{bc}$ denote key bits 00, 01, 10 and 11, respectively. Bob performs *a* measurement on photons *b* and *c*. Photon *c* is the object to be teleported. At the same time of teleporting the state of photon *c* over the quantum channel, Bob sends photon d to Alice via an optical fibre.

Step 3:

If Alice receives photon *d*, she calculates and records the value of $_a\langle\phi|\phi\rangle_d$ then Alice must get one of the four possible results $-\alpha^2 - \beta^2 = -1$, $-\alpha^2 + \beta^2$, $2\alpha\beta$ and 0 if Eve does not disturb the channel. Correspondingly, the four possible results -1, $-\alpha^2 + \beta^2$, $2\alpha\beta$ and 0 denote key bits 00, 01, 10 and 11, respectively.

Bob chooses the amplitudes α and β in such a way which makes -1, $-\alpha^2 + \beta^2$, $2\alpha\beta$ and 0 different from each other. Therefore, as long as Bob has teleported the state of photon *c* and Alice has received photon *d* from Bob, both Alice and Bob will obtain their key bits. For example, if Bob gets the result of $|\psi^+\rangle_{bc}$ after teleportation, Bob obtains key bits 01, and then Alice achieves the same key bits 01 since the result is $-\alpha^2 + \beta^2$ when there exists no disturbance from Eve.

Step 4:

Repeating the above three steps, Alice records a series of values and Bob can obtain a string of key bits.

Step 5:

Bob announces the amplitudes α and β of each photon state he sent to Alice. Then Alice judges whether each record is legitimate or not, and keeps the legitimate records as key bits and announces the illegitimate records to Bob. According to Alice's announcement, Bob discards the corresponding key bits and chooses the left bits as key bits.

Thus, Alice and Bob share a private key. For further information we can refer to [38]-[40]. The QKA protocol is simpler than the BB84 protocol [41], the EPR protocol [42] and the B92 protocol [43], where Alice and Bob communicate classically their choice of basis and discard all measurement results where different bases were used.

VI. Recent Developments In Entanglement And Q-Teleportation Physics

Quantum teleportation physics is still in primary stage. Technical applications of entanglement and q-Teleportation are just becoming conceptualized. An important application of quantum entanglement and q-Teleportation was the discovery made by Shor [44], [45] that computation with quantum states instead of classical bits can result in large savings in computation time. Here we present some instances of recent developments in Entanglement and q-Teleportation:

a. Experiments based on present fiber technology have demonstrated that entangled photon pairs can be separated by distances ranging from several hundreds of meters up to 10 km [46].
b. Quantum error correction codes exist, whereby qubits are passed through a circuit (the quantum analogue of logic gates) that will successfully fix an error in any one of the qubits without actually reading what all the individual qubit states are; no qubit cloning is required.
c. A completely secure quantum key can be generated and distributed (for communication and decoding of encrypted messages) using entangled photons has been demonstrated [5]-[7] any eavesdropper's attempt to intercept the quantum key will alter the contents in a detectable way, enabling users to discard the compromised parts of the data.

d. Generation of entanglement and teleportation by Parametric Down-Conversion [47], [48] – When a laser beam passes through a nonlinear β-barium borate or BBO crystal. Inside the crystal (BBO, for example) an ultraviolet photon (λ = 490 nm) may spontaneously split into two lower energy infrared photons (λ = 780 nm), this process is called parametric down-conversion. The two "down-conversion" photons come out as independent beams with orthogonal polarizations (horizontal or vertical).
e. Teleportation of squeezed states of light and continuous quantum state variables [26], [49]-[55] - Using squeezed light EPR entangled beams can be generated. One beam is sent to Alice and another to Bob. A third beam which is a coherent state of unknown complex amplitude is teleported to Bob with high fidelity only achievable through the use of quantum entanglement. Here this third beam is input. By combining two beams of squeezed light at a 50/50 beam splitter entangled EPR beams are generated. One EPR beam that propagates to Alice's sending station is combined at a 50/50 beam splitter with the unknown input state. Alice performs Bell-state measurement on the amplitudes of the combined state. He then sends the measurements output to Bob using classical channel. Bob uses this information to perform phase-space displacement and gets the quantum state identical to Alice's input beam.
f. Entanglement of Atoms [56], [57] - Using rubidium atoms prepared in circular Rydberg states it has been demonstrated experimentally the EPR entanglement at the level of atoms. In the experiment tow entangled photons were produced of them one atom in a round state and the other atom in excited state and they were physically separated so that entanglement is non-local. When measurement is made on one atom and if that atom is in ground state then the other atom instantaneously will be in the excited state.
g. Teleportation of an Atomic State via Cavity Decay [57], [58] - State of a trapped in a cavity can be teleported to a second atom trapped in a distant cavity by detecting photon decays from the cavities.
h. Biological Quantum Teleportation [59] - Mavromatos et al. [59] proposed a model which predicts dissipationless energy transfer along shielded macromolecules at near room temperatures as well as quantum teleportation of states across microtubules and perhaps neurons. It is proposed that under certain circumstances it is in principle possible to obtain the necessary isolation against environmental decoherence.
i. Teleportation of a laser beam with embedded radio signal [55] - In laboratory experiment experts embedded a radio signal into a laser beam. Then they disintegrated the beam and reassembled in one meter away. This process was done instantaneously. In the teleportation process the laser beam was destroyed but the radio signal survived. Though in teleportation process laser beam destroyed but its encoded message survived. This system could be used to transport secure data and hence it could possible to make a perfect cryptography system.
j. Entanglement and Teleportation of a Macroscopic Ensemble of Atoms [60] - Depending upon the earlier work of Hald et al. [61] and Sackett et al. [57] experts experimentally demonstrated the entanglement of a cesium gas sample containing ≈ 1012 atoms.
k. Entanglement/teleportation of internal state and external motion information of atoms [62] – It has been proposed for an experiment that can transfer an atom's full information, including its "external" states, such as its energy of motion. This procedure replicates the quantum features of the external motion of a particle.
l. Laser-like Amplification of Entangled Particles and Entangled-Photon Lasers [63] - To increase the number of entangled photons researchers put mirrors beyond the crystal so that the laser pulse and entangled pair could reflect, and have the chance to interact. The entangled pair and reflected laser pulse interfere constructively to generate fourfold more tow-photon pairs or interfere destructively to create zero pairs. By this process the researchers increased production of two-photon entangled pairs, and also could generate rare states such as four-photon entangled quarters. This achievement could represent a stem towards and entangled-photon laser.

VII. Conclusion

The field of quantum teleportation has made a remarkable progress ever since it has been initiated. We have presented concept on Quantum Teleportation which is based on the well-known concept of Quantum Entanglement that Einstein called "spooky action at a distance" in his EPR paper [12]. We showed that entangle particles can serve as "transporters" that is by introducing a third "message" particle to one o the entangle particles one could transfer its properties to the other one. We have listed the recent developments in Entanglement and Quantum Teleportation Physics and saw that information can be teleported over 40 km using existing technology (H. Everitt, Army Research Office, 2000). Here in this paper have tried to make a simple framework for using Teleportation in quantum key distribution system that will help the computer scientists and engineers to forward in the regime of quantum key distribution.

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